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HYDJET++ heavy ion event generator and its applications for RHIC and LHC

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The heavy ion event generator HYDJET++ is presented. HYDJET++ simulates relativistic heavy ion AA collisions as a superposition of the soft, hydro-type state and the hard state resulting from multi-parton fragmentation. This model is the development and continuation of HYDJET event generator. The hard parts of HYDJET and HYDJET++ are identical. The soft part of HYDJET++ contains the following important additional features as compared with HYDJET: resonance decays and more detailed treatment of thermal and chemical freeze-out hypersurfaces. HYDJET++ is capable of reproducing the bulk properties of heavy ion collisions at RHIC (hadron spectra and ratios, radial and elliptic flow, femtoscopic momentum correlations), as well as high-p_T hadron spectra. Some applications of HYDJET++ at LHC are discussed.

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1. Introduction

One of the basic tasks of modern high energy physics is the study of the fundamental theory of strong interaction (Quantum Chromodynamics, QCD) in new, unexplored extreme regimes of super-high densities and temperatures through the investigation of the properties of multi-particle systems produced in high-energy nuclear collisions [1, 2]. Ongoing and future experimental heavy ion studies require the development of new Monte-Carlo (MC) event generators and improvement of existing ones. Especially for experiments at the CERN Large Hadron Collider (LHC), because of very high parton and hadron multiplicities, one needs fast (but realistic) MC tools for heavy ion event simulations [3, 4, 5, 6]. A realistic MC event generator should include a maximum possible number of observable physical effects which are important to determine the event topology: from the bulk properties of soft hadroproduction (domain of low transverse momenta $p_T \lesssim 1\text{GeV}/c$) such as collective flows, to hard multi-parton production in hot and dense QCD-matter, which reveals itself in the spectra of high-p_T particles and hadronic jets. However, in most of the available MC heavy ion event generators, the simultaneous treatment of collective flow effects for soft hadroproduction and hard multi-parton in-medium production is absent.

HYDJET++ event generator [7, 8] includes detailed treatment of soft hadroproduction as well as hard multi-parton production, and takes into account medium-induced parton rescattering and energy loss. The heavy ion event in HYDJET++ is the superposition of two independent components: the soft, hydro-type state and the hard state resulting from multi-parton fragmentation. HYDJET++ model is the development and continuation of HYDJET event generator [9, 10, 11, 12], and it contains the important additional features for the soft component: resonance decays and more detailed treatment of thermal and chemical freeze-out hypersurfaces [13, 14]. The main program HYDJET++ is written in the object-oriented C++ language under the ROOT environment [15].

2. Physics model and simulation procedure

The soft and hard components in HYDJET++ are treated independently. When the generation of soft and hard components in each event at given b is completed, the event record (information about coordinates and momenta of primordial particles, decay products of unstable particles and stable particles) is formed as the junction of these two independent event outputs.

The details on physics model and simulation procedure of HYDJET++ can be found in the corresponding manual [7]. The main features of HYDJET++ model are listed only very briefly in this section.

2.1 Hard multi-jet production

The model for the hard multi-parton part of HYDJET++ event is the same as that for HYDJET event generator, and it based on PYQUEN partonic energy loss model [9, 10, 11]. The approach to the description of multiple scattering of hard partons in the dense QCD-matter (such as quark-gluon plasma) is based on the accumulative energy loss via the gluon radiation being associated with each parton scattering in the expanding quark-gluon fluid and includes the interference effect (for the emission of gluons with a finite formation time) using the modified radiation spectrum dE/dl as a function of decreasing temperature T. The model takes into account radiative and

collisional energy loss of hard partons in longitudinally expanding quark-gluon fluid, as well as realistic nuclear geometry.

The Fortran routine for single hard nucleon-nucleon sub-collision PYQUEN [16] was constructed as a modification of the jet event obtained with the generator of hadron-hadron interactions PYTHIA_6.4 [17]. The event-by-event simulation procedure in PYQUEN includes *1)* generation of initial parton spectra with PYTHIA and production vertexes at given impact parameter; *2)* rescattering-by-rescattering simulation of the parton path in a dense zone and its radiative and collisional energy loss; *3)* final hadronization according to the Lund string model for hard partons and in-medium emitted gluons. Then the PYQUEN multi-jets generated according to the binomial distribution are included in the hard part of the event. The mean number of jets produced in an AA event is the product of the number of binary NN sub-collisions at a given impact parameter and the integral cross section of the hard process in *NN* collisions with the minimum transverse momentum transfer $p_T^{\rm min}$. In order to take into account the effect of nuclear shadowing on parton distribution functions, the impact parameter dependent parameterization obtained in the framework of Glauber-Gribov theory [18] is used.

Note that some different approaches for MC treatment of partonic energy loss, such as codes YaJEM [19], JEWEL [20] and Q-PYTHIA [21] have been presented during this Workshop.

2.2 Soft "thermal" hadron production

The soft part of HYDJET++ event is the "thermal" hadronic state generated on the chemical and thermal freeze-out hypersurfaces obtained from the parameterization of relativistic hydrodynamics with preset freeze-out conditions (the adapted C++ code FAST MC [13, 14]). Hadron multiplicities are calculated using the effective thermal volume approximation and Poisson multiplicity distribution around its mean value, which is supposed to be proportional to the number of participating nucleons at a given impact parameter of AA collision. The fast soft hadron simulation procedure includes *1)* generation of the 4-momentum of a hadron in the rest frame of a liquid element in accordance with the equilibrium distribution function; *2)* generation of the spatial position of a liquid element and its local 4-velocity in accordance with phase space and the character of motion of the fluid; *3)* the standard von Neumann rejection/acceptance procedure to account for the difference between the true and generated probabilities; *4)* boost of the hadron 4-momentum in the center mass frame of the event; *5)* the two- and three-body decays of resonances with branching ratios taken from the SHARE particle decay table [22]. The high generation speed in HYDJET++ is achieved due to almost 100% generation efficiency of the "soft" part because of the nearly uniform residual invariant weights which appear in the freeze-out momentum and coordinate simulation.

Let us indicate some physical restrictions of the model. HYDJET++ is only applicable for symmetric AA collisions of heavy (A $\gtrsim$ 40) ions at high energies ($\sqrt{s} \gtrsim$ 10 GeV). Since the hydro-type approximation for heavy ion collisions is considered to be valid for central and semi-central collisions, the results obtained for very peripheral collisions (with impact parameter of the order of two nucleus radii, $b \sim 2R_A$) may be not adequate. Nor do we expect a correct event description in the region of very forward rapidities, where the other mechanisms of particle production, apart from hydro-flow and jets, may be important.

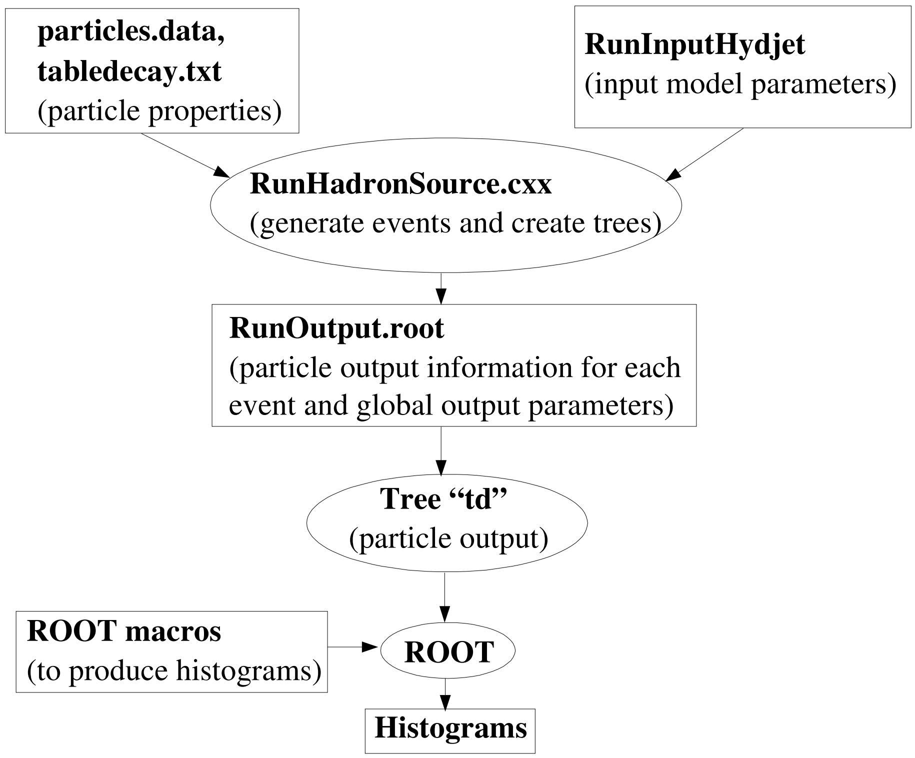

Figure 1: The block structure of HYDJET++.

3. HYDJET++ software structure

The basic frameworks of HYDJET++ are preset by the object-oriented C++ language and the ROOT environment [15]. There is also the Fortran-written part [12] which is included in the generator structure as a separate directory. The block structure of HYDJET++ is shown in Figure 1. The main program elements are particle data files, input and output files, C++ and Fortran routines.

The information regarding the particle species included in the HYDJET++ event is stored in the files `particles.data` and `tabledecay.txt`. The `particles.data` file contains the definition (PDG code) and physical properties (mass, decay width, spin, isospin, valence quark composition) of 360 stable hadrons and resonances. The `tabledecay.txt` file contains decay channels and branching ratios. The structure of these files is the same as that in SHARE particle data table [22] and in event generator THERMINATOR [23].

Run of HYDJET++ is controlled by the file `RunInputHydjet` for different type of input parameters. The input file contains 7 input parameters (number of events to generate, beam c.m.s. energy per nucleon pair in GeV, atomic weight of nuclei and parameters to specify the type of centrality selection) and 18 free model parameters, which can be varied by the user from their default values (chemical potentials, chemical and thermal freeze-out temperatures, space-time scales of soft hadron emission, maximal longitudinal and transverse flow rapidities, momentum and coordinate azimuthal anisotropy parameters, PYQUEN energy loss model parameters). A number of important PYTHIA parameters also may be changed/specified in `RunInputHydjet` file. There are also 10 flags to specify different physical model scenarios for soft and/or hard components. In particular,

the activation of some flags allows one to calculate a few model parameters, and so to reduce the number of independent free parameters (down to 12 at the minimum). Two additional files with the optimized parameters for Au+Au collisions at $\sqrt{s} = 200A$ GeV (`RunInputHydjetRHIC200`) and for Pb+Pb collisions at $\sqrt{s} = 5500A$ GeV (`RunInputHydjetLHC5500`) are available in the distribution package. The default parameters for `RunInputHydjetRHIC200` were obtained by fitting RHIC data to various physical observables. The default parameters for `RunInputHydjetLHC5500` represent our rough extrapolation from RHIC to LHC energy.

The program output is directed to the ROOT file `RunOutput.root`. The output file contains a tree named `td`, which keeps the entire event record including primary particles and decay products with their coordinates and momenta information. Each decay product contains the unique index of its parent particle so that the entire event history may be obtained. Beside particle information, the output file contains also a number of global output parameters for each event (generated value of impact parameter, total inelastic and hard scattering cross sections, hadron event multiplicities of hard and soft components, numbers of binary NN sub-collisions and nucleons-participants).

HYDJET++ includes 17 C++ source files (4 main modules and 13 service modules placed in the main directory) and 3 Fortran files (placed in the separate directory). The size of the distribution package is 3.5 MBytes directory and 800 kBytes compressed archive (without ROOT libraries). The generation of 100 central (0−5%) Au+Au events at $\sqrt{s} = 200A$ GeV (Pb+Pb events at $\sqrt{s} = 5500A$ GeV) with default input parameters takes about 7 (85) minutes on a PC 64 bit Intel Core Duo CPU @ 3 GHz with 8 GB of RAM memory under Red Hat Enterprise. Then the output file created by the code in ROOT tree format will require 40 (190) MBytes of the disk space.

4. Validation of HYDJET++ with experimental RHIC data

It was demonstrated in [13, 14] that FAST MC model can describe well the bulk properties of hadronic state created in Au+Au collisions at RHIC at $\sqrt{s} = 200A$ GeV (such as particle number ratios, low-p$_T$ spectra, elliptic flow coefficients $v_2(p_T, b)$, femtoscopic correlations in central collisions), while HYDJET model is capable of reproducing the main features of jet quenching pattern at RHIC (high-p_T hadron spectra and the suppression of azimuthal back-to-back correlations) [9]. Since soft and hard hadronic states in HYDJET++ are simulated independently, a good description of hadroproduction at RHIC in a wide kinematic range can be achieved, moreover a number of improvements in FAST MC and HYDJET have been done as compared to earlier versions. A number of input parameters of the model can be fixed from fitting the RHIC data to various physical observables.

1. **Ratio of hadron abundances.** It is well known that the particle abundances in heavy ion collisions in a wide energy range can be reasonable well described within statistical models based on the assumption that the produced hadronic matter reaches thermal and chemical equilibrium. The thermodynamical potentials $\widetilde{\mu_B} = 0.0285$ GeV, $\widetilde{\mu_S} = 0.007$ GeV, $\widetilde{\mu_Q} = -0.001$, the strangeness suppression factor $\gamma_s = 1$, and the chemical freeze-out temperature $T^{\rm ch} = 0.165$ GeV have been fixed in [13] from fitting the RHIC data to various particle ratios near mid-rapidity in central Au+Au collisions at $\sqrt{s} = 200A$ GeV (π^-/π^+, $\bar{p}/\pi^-$, K^-/K^+, K^-/π^-, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$, $\bar{\Lambda}/\Lambda$, $\bar{\Xi}/\Xi$, ϕ/K^-, Λ/p, Ξ^-/π^-).

2. **Low-p_T hadron spectra.** Transverse momentum p_T and transverse mass m_T hadron spectra (π^+, K^+ and p with $m_T < 0.7$ GeV/c^2) near mid-rapidity at different centralities of Au+Au collisions at $\sqrt{s} = 200A$ GeV were analyzed in [14]. The slopes of these spectra allow the thermal freeze-out temperature $T^{\rm th} = 0.1$ GeV and the maximal transverse flow rapidity in central collisions $\rho_u^{\rm max}(b=0) = 1.1$ to be fixed.

3. **Femtoscopic correlations.** Because of the effects of quantum statistics and final state interactions, the momentum (HBT) correlation functions of two or more particles at small relative momenta in their c.m.s. are sensitive to the space-time characteristics of the production process on the level of fm. The space-time parameters of thermal freeze-out region in central Au+Au collisions at $\sqrt{s} = 200A$ GeV have been fixed in [14] by means of fitting the three-dimensional correlation functions measured for $\pi^+\pi^+$ pairs and extracting the correlation radii $R_{\rm side}$, $R_{\rm out}$ and $R_{\rm long}$: $\tau_f(b=0) = 8$ fm/c, $\Delta\tau_f(b=0) = 2$ fm/c, $R_f(b=0) = 10$ fm.

4. **Pseudorapidity hadron spectra.** The PHOBOS data on η-spectra of charged hadrons [24] at different centralities of Au+Au collisions at $\sqrt{s} = 200A$ GeV have been analyzed to fix the particle densities in the mid-rapidity region and the maximum longitudinal flow rapidity $\eta_{\rm max} = 3.3$ (Fig. 2). Since mean "soft" and "hard" hadron multiplicities depend on the centrality in different ways (they are roughly proportional to $\overline{N_{\rm part}(b)}$ and $\overline{N_{\rm bin}(b)}$ respectively), the relative contribution of soft and hard parts to the total event multiplicity can be fixed through the centrality dependence of $dN/d\eta$. The corresponding contributions from hydro- and jet-parts are determined by the input parameters $\mu_\pi^{\rm eff~th} = 0.053$ GeV and $p_T^{\rm min} = 3.4$ GeV/c respectively.

5. **High-p_T hadron spectra.** High transverse momentum hadron spectra ($p_T \gtrsim 2-4$ GeV/c) are sensitive to parton production and jet quenching effects. Thus fitting the measured high-p_T tail allows the extraction of PYQUEN energy loss model parameters. We assume the QGP formation time $\tau_0 = 0.4$ fm/c and the number of active quark flavours $N_f = 2$. Then the reasonable fit of STAR data on high-p_T spectra of charged pions at different centralities of Au+Au collisions at $\sqrt{s} = 200A$ GeV [25] is obtained with the initial QGP temperature $T_0 = 0.3$ GeV (Fig. 3).

6. **Elliptic flow.** The elliptic flow coefficient v_2 (which is determined as the second-order Fourier coefficient in the hadron distribution over the azimuthal angle φ relative to the reaction plane angle ψ_R, so that $v_2 \equiv \langle \cos 2(\varphi - \psi_R) \rangle$) is an important signature of the physics dynamics at early stages of non-central heavy ion collisions. According to the typical hydrodynamic scenario, the values $v_2(p_T)$ at low-p_T ($\lesssim 2$ GeV/c) are determined mainly by the internal pressure gradients of an expanding fireball during the initial high density phase of the reaction (and it is sensitive to the momentum and azimuthal anisotropy parameters δ and ε in the frameworks of HYDJET++), while elliptic flow at high-p_T is generated in HYDJET++ (as well as in other jet quenching models) due to the partonic energy loss in an azimuthally asymmetric volume of QGP. Figure 4 shows the measured by the STAR Collaboration transverse momentum dependence of the elliptic flow coefficient v_2 of charged hadrons in Au+Au collisions at $\sqrt{s} = 200A$ GeV for two centrality sets [26]. The values of

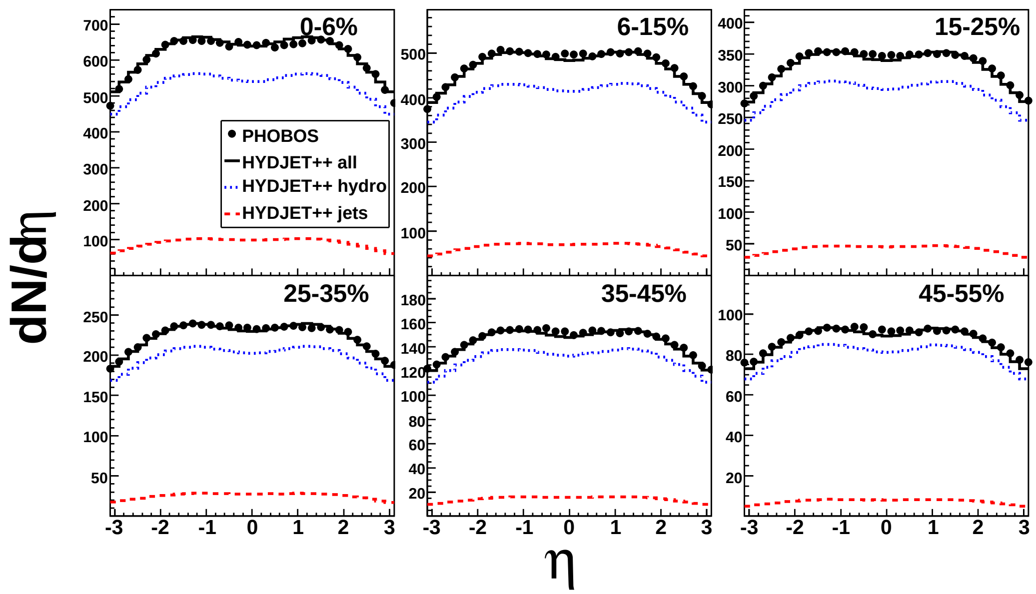

Figure 2: The pseudorapidity distribution of charged hadrons in Au+Au collisions at $\sqrt{s} = 200A$ GeV for six centrality sets. The points are PHOBOS data [24], histograms are the HYDJET++ calculations (solid – total, dotted – hydro part, dashed – jet part).

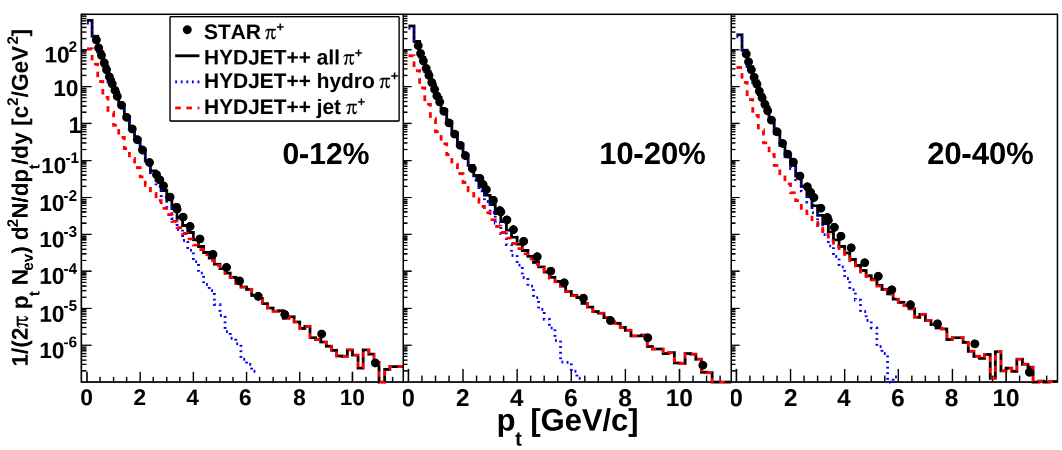

Figure 3: The transverse momentum distribution of positively charged pions in Au+Au collisions at $\sqrt{s} = 200A$ GeV for three centrality sets. The points are STAR data [25], histograms are the HYDJET++ calculations (solid – total, dotted – hydro part, dashed – jet part).

δ and ε are estimated for each centrality. Note that the choice of these parameters does not affect any azimuthally integrated physics observables (such as hadron multiplicities, η- and p_T-spectra, etc.), but only their differential azimuthal dependences.

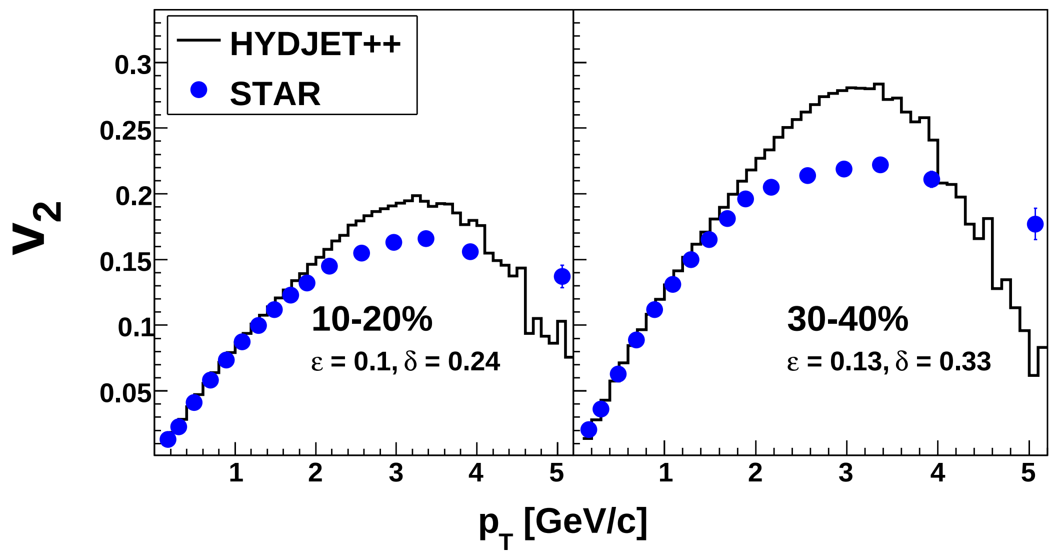

Figure 4: The transverse momentum dependence of the elliptic flow coefficient v_2 of charged hadrons in Au+Au collisions at $\sqrt{s} = 200A$ GeV for two centrality sets. The points are STAR data [26], histograms are the HYDJET++ calculations.

5. Simulations with HYDJET++ at LHC

The heavy ion collision energy at LHC a factor of 30 larger then that at RHIC, thereby allows one to probe new frontiers of super-high temperature and (almost) net-baryon free QCD. The emphasis of the LHC heavy ion data analysis (at $\sqrt{s} = 5.5$ TeV per nucleon pair for lead beams) will be on the perturbative, or hard probes of the QGP (quarkonia, jets, photons, high-p$_T$ hadrons) as well as on the global event properties, or soft probes (collective radial and elliptic flow effects, hadron multiplicity, transverse energy densities and femtoscopic momentum correlations). It is expected that at LHC energies the role of hard and semi-hard particle production will be significant even for the bulk properties of created matter. HYDJET++ seems to be an effective simulation tool to analyze the influence of in-medium jet fragmentation on various physical observables.

Figures 5 and 6 show the pseudorapidity distribution of charged hadrons and transverse momentum distribution of pions respectively obtained with HYDJET++ default settings (in particular, $p_T^{\rm min} = 7$ GeV/c) for 5% most central Pb+Pb events. The estimated contribution of hard component to the total event multiplicity is on the level $\sim 55\%$ here, what is much larger than as compared with RHIC ($\sim 15\%$, see Fig. 2). Of course, this number is very sensitive to the parameter $p_T^{\rm min}$ — minimal p_T of "non-thermalized" parton-parton hard scatterings. For example, increasing the value $p_T^{\rm min}$ up to 10 GeV/c results in decreasing this contribution down to $\sim 25\%$.

Some applications of HYDJET++ for high-p$_T$ studies at the LHC have been presented during this Workshop [27, 28]. In this paper we discuss one another striking example: the influence of jets on femtoscopic momentum correlations (HBT-radii) [29]. Since HYDJET++ specifies the space-time structure of a hadron emission source (for soft and for hard components as well), the momentum correlation function can be introduced by the special weighting procedure [30, 31]. Knowing the information on final particle four-momenta p_i and four-coordinates x_i of the emis-

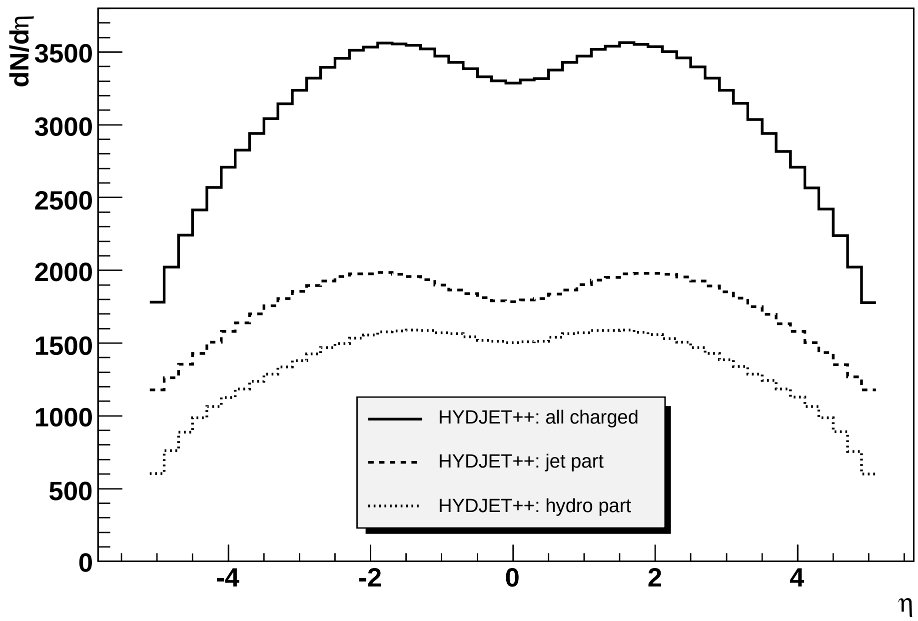

Figure 5: The pseudorapidity distribution of charged hadrons in 5% most central Pb+Pb collisions at $\sqrt{s} = 5500A$ GeV (solid – total, dotted – hydro part, dashed – jet part), $p_T^{\min} = 7$ GeV/c.

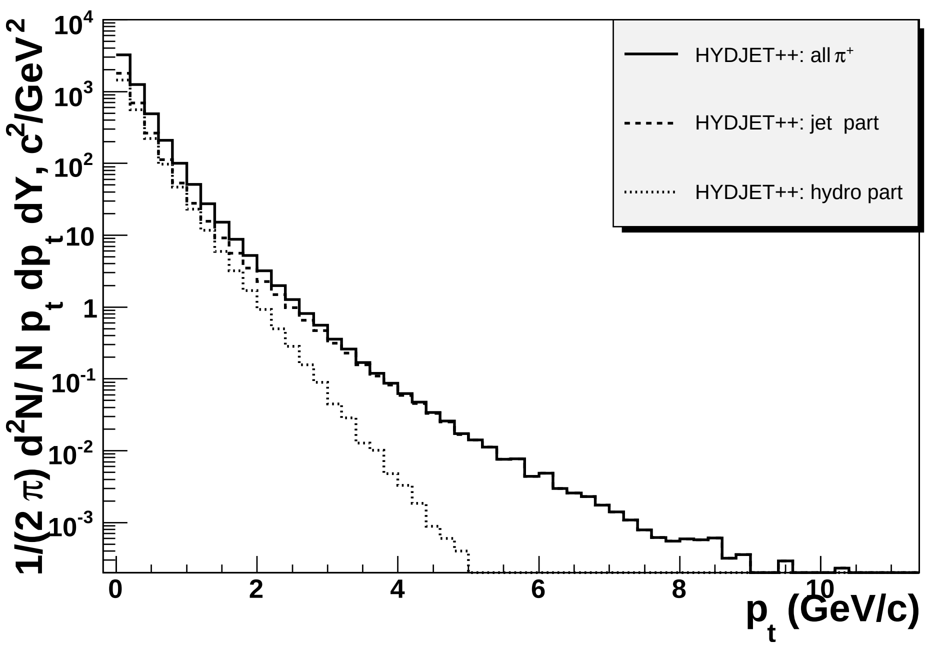

Figure 6: The transverse momentum distribution of pions in 5% most central Pb+Pb collisions at $\sqrt{s} = 5500A$ GeV (solid – total, dotted – hydro part, dashed – jet part), $p_T^{\min} = 7$ GeV/c.

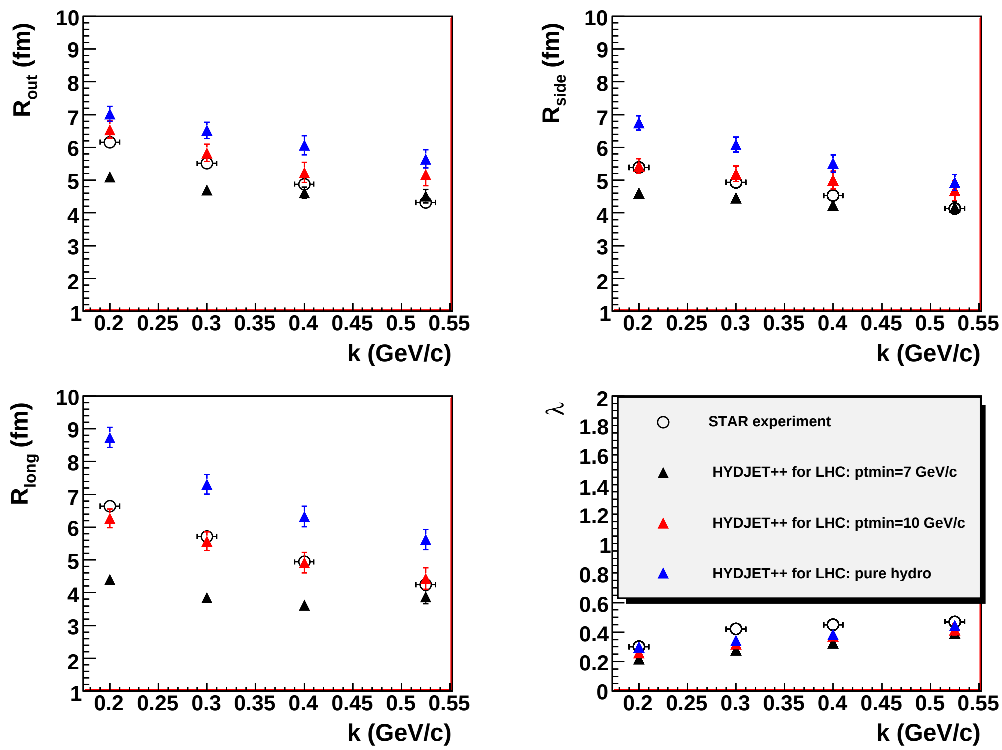

Figure 7: The $\pi^{\pm}\pi^{\pm}$ correlation radii and the strength parameter λ at mid-rapidity as the function of relative pion momentum k in 5% most central Pb+Pb collisions at $\sqrt{s} = 5500A$ GeV (black triangles – $p_T^{\rm min} = 7$ GeV/c, red triangles – $p_T^{\rm min} = 10$ GeV/c, blue triangles – pure hydro). The open circles are STAR data [32].

sion points allows one to calculate the correlation function with the help of the weight procedure, assigning a weight to a given particle combination accounting for the effects of quantum statistics:

$$w = 1 + \cos(q \cdot \Delta x), \tag{5.1}$$

where $q = p_1 - p_2$ and $\Delta x = x_1 - x_2$. Then the correlation function is defined as a ratio of the weighted histogram of the pair kinematic variables to the unweighted one. The corresponding correlation widths are parameterized in terms of the Gaussian correlation radii R_i,

$$CF(p_1, p_2) = 1 + \lambda \exp(-R_{\rm out}^2 q_{\rm out}^2 - R_{\rm side}^2 q_{\rm side}^2 - R_{\rm long}^2 q_{\rm long}^2 - 2R_{\rm out,long}^2 q_{\rm out} q_{\rm long}) \ , \tag{5.2}$$

where $\mathbf{q} = (q_{\rm out}, q_{\rm side}, q_{\rm long})$ is the relative three-momentum vector of two identical particles and λ is the correlation strength. The *out* and *side* denote the transverse, with respect to the reaction axis, components of the vector $\mathbf{q}$; the out direction is parallel to the transverse component of the pair three–momentum.

The correlation functions of two identical charged pions have been calculated for 5% most central Pb+Pb events at two values of $p_T^{\rm min}$: 7 GeV/c and 10 GeV/c. Figure 7 shows the corresponding values of fitted correlation radii and strength parameter as a function of relative pion momentum in comparison with those measured by STAR collaboration [32]. One can see that the "pure hydro" scenario results in some increasing of correlation radii at LHC in comparison with

RHIC, as it could be naively expected from the appropriate extrapolation of the volume parameters [6]. However increasing the contribution of hard component to the total event multiplicity results in decreasing the correlation radii due to the fact that "jet-induced" hadrons are emitted on much shorter space-time scales than "thermal" particles. HYDJET++ predicts that the correlation radii at LHC become comparable with those at RHIC for $\sim 25\%$ contribution of hard component ($p_T^{\rm min} = 10$ GeV/c), and may be even less than at RHIC for larger contribution of hard component ($p_T^{\rm min} < 10$ GeV/c). On the other hand, the influence of hard component on correlation radii at RHIC was found to be negligible. Thus the observation of reducing the correlation radii as one moves from RHIC to LHC could manifest the strong influence of in-medium jet fragmentation on the bulk event topology.

6. Summary

Among other heavy ion event generators, HYDJET++ focusses on the detailed simulation of jet quenching effect basing on the partonic energy loss model PYQUEN, and also reproducing the main features of nuclear collective dynamics by fast (but realistic) way. The final hadron state in HYDJET++ represents the superposition of two independent components: hard multi-parton fragmentation and soft hydro-type part. The main program is written in the object-oriented C++ language under the ROOT environment. This model is the development and continuation of HYDJET event generator. The hard part of HYDJET++ is identical to the hard part of Fortran-written HYDJET and it is included in the generator structure as a separate directory. The soft part of HYDJET++ is the "thermal" hadronic state generated on the chemical and thermal freeze-out hypersurfaces obtained from the parameterization of relativistic hydrodynamics with preset freeze-out conditions. It contains the important additional features as compared with HYDJET: resonance decays and more detailed treatment of thermal and chemical freeze-out hypersurfaces. HYDJET++ is capable of reproducing the bulk properties of heavy ion collisions at RHIC (hadron spectra and ratios, radial and elliptic flow, femtoscopic momentum correlations), as well as high-p_T hadron spectra.

HYDJET++ is an effective simulation tool to analyze the influence of in-medium jet fragmentation on various physical observables at the LHC. In particular, the spectacular prediction of HYDJET++ is reducing the femtoscopic correlation radii in heavy ion collisions as one moves from RHIC to LHC due to the significant contribution of (semi-)hard component to the space-time structure of the hadron emission source.

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